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Role of Artificial Intelligence in Understanding and Managing Infertility: From Diagnosis to Therapeutics

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ABSTRACT

Infertility is a widespread problem experienced by many couples around the world, resulting from multiple factors including genetic, hormonal, environmental, and lifestyle. The use of Artificial Intelligence (AI) has significantly changed how infertility is understood, diagnosed, and treated. This study explores how AI, including deep learning, machine learning, and predictive analytics, can improve reproductive health care. High accuracy in analyzing medical images, semen analysis, and ovarian reserve by AI algorithms has enabled early and accurate detection of male and female infertility. By assisting with embryo selection, predicting IVF outcomes, and developing individualized treatment plans, AI has played a significant role in improving ART success rates. AI can leverage large quantities of proteomics, genomics, and clinical data to discover new biomarkers and treatment targets. However, lack of standardization, algorithmic bias, and data privacy remain significant barriers to clinical implementation. Regardless, AI has great potential for transforming infertility services through precision medicine. Future research should prioritize validating AI applications, exploring ethical implications, and integrating AI into standard clinical procedures.

1. Introduction

Infertility affects millions worldwide and is a complex condition affecting reproductive health in both males and females. Clinically, it is defined as the inability to achieve pregnancy after at least twelve months of regular unprotected intercourse, a WHO definition used in medical practice and epidemiological studies worldwide. Infertility remains a major public health concern, with approximately one in six sexually active people experiencing it during their reproductive years; while rates and causes vary by region and socioeconomic strata, the overall impact is significant regardless of economic standing [1]. Two main types are recognized: primary infertility (never achieved pregnancy) and secondary infertility (prior pregnancy but subsequent inability to conceive). Causes include female, male, combined, and unexplained factors. Male-factor infertility contributes substantially, with estimates of 30–50% of cases, arising from problems with sperm production or quality, hormonal imbalances, congenital issues, and lifestyle factors such as smoking and obesity [2-4]. Female infertility involves diverse biological and physiological issues including anovulation (e.g., PCOS), ovulatory disturbances, tubal factors, endometriosis, uterine abnormalities, advanced maternal age, and endocrine/metabolic disorders such as hypothyroidism, obesity, and diabetes. Environmental, social, and lifestyle stressors further raise prevalence globally, motivating a multidisciplinary approach across research, healthcare policy, and clinical care. The emotional and

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psychosocial impact is well documented, with anxiety, depression, and stress affecting relationships and quality of life, compounded by the stigma of childlessness in certain cultures [5,6]. Methodological inconsistency in defining and measuring infertility complicates global estimates, and systematic reviews emphasize the need for standardized methodologies [7].

2. Artificial Intelligence in Infertility Diagnosis

AI has rapidly emerged as a transformative approach to diagnosing infertility, helping clinicians overcome long-standing limitations of traditional methods such as subjective semen evaluation and manual interpretation of reproductive imaging. Conventional diagnosis relies on laboratory tests, physical examination, and subjective interpretation of reproductive parameters, with significant inter-observer variation and limited precision causing inconsistencies. Machine learning (ML) and deep learning (DL) have markedly improved the precision and consistency of interpreting complex reproductive data [8]. A key area is semen analysis, a core diagnostic test for male infertility. Traditional analysis of sperm count, motility, and morphology suffers from inter- and intra-observer variability and poor reproducibility. AI-based computer-aided sperm analysis (CASA) using convolutional neural networks (CNNs) and advanced image processing assesses sperm rapidly and objectively; a recent systematic review reported morphology classification accuracy up to 96.8%, greatly reducing subjective error [9-11]. Deep-learning models such as a modified U-Net improve sperm cell segmentation and detection from microscopy video, aiding diagnosis, treatment planning, and outcomes. AI also improves female reproductive diagnosis, evaluating hormonal profiles, ovarian reserve markers, and imaging (e.g., ultrasound) to identify conditions such as PCOS, endometriosis, or diminished ovarian reserve, and integrating clinical, biochemical, and imaging data to create individualized fertility assessments [12].

2.1. AI-Based Semen Analysis

Male infertility diagnostics are shifting toward AI-based semen analysis. Manual assessment of sperm count, motility, and morphology suffers from high inter- and intra-observer variability; despite WHO standardization guidelines, morphological evaluation shows only ~40–60% concordance between observers. Deep-learning models, especially CNNs, now automate detection, classification, and measurement of sperm features for more objective, rapid assessment, extracting morphological and motility data from microscope images or video without extensive manual effort [9,10,13]. Models using ResNets with attention mechanisms achieve high precision (~97%), though some report ~55% depending on validation datasets; frameworks adding segmentation before classification improve accuracy. For motility, CNN-based analysis of high-speed video correlates strongly with manual assessment (Pearson r ~0.88–0.89) [9,14]. Emerging tools assess higher-level function, including non-destructive evaluation of sperm DNA fragmentation through imaging, improving sperm selection for IVF and ICSI. AI also offers speed and scalability, processing millions of sperm per sample in minutes, and clinicians report identifying viable sperm in difficult cases such as azoospermia. AI-enhanced CASA provides objective metrics such as curvilinear velocity and beat cross frequency, improving diagnostic accuracy and laboratory workflow efficiency [10,11,15,16].

2.2. Hormonal and Imaging Data Analysis

AI enhances analysis of hormonal profiles and reproductive imaging for female infertility. ML models integrate ovarian reserve markers (such as AMH and antral follicle count), endocrine data, and ultrasound to detect conditions including PCOS and diminished ovarian reserve, improving accuracy and consistency over conventional interpretation. Deep-learning analysis of ultrasound and other imaging extracts subtle features predictive of reproductive status, supporting individualized assessment and earlier intervention while reducing operator-dependent variability [17,19,20].

3. Artificial Intelligence in Assisted Reproductive Technology (ART)

ART, including IVF and associated procedures, has transformed fertility treatment, yet success rates remain modest at roughly 30% per cycle globally, varying with age and clinic type. Outcomes depend heavily on

clinician experience and subjective judgment, particularly in embryo selection and treatment planning. AI and ML now provide enhanced decision-making, precision, and personalization. In embryo selection, advanced image analysis and deep-learning models objectively evaluate embryo morphology and predict implantation potential, outperforming manual grading by analyzing still images or time-lapse sequences and reducing subjective variability; a systematic review found AI-based evaluation significantly improves prediction of clinical outcomes and morphological quality versus embryologist assessment [21-25]. Multimodal AI fusing static and time-lapse imaging with structured clinical data predicts implantation and pregnancy more accurately than traditional methods and refines selection protocols. AI also improves ovarian stimulation and follicular monitoring to optimize oocyte maturation timing, with explainable AI on multi-center IVF datasets identifying follicular features predictive of oocyte retrieval and live birth. During ICSI, AI ranks individual sperm by motility, morphology, and viability in real time, potentially improving fertilization rates and reducing operator variability; clinical validation for live births requires continued research [18,26,27]. Predictive models built from large ART datasets estimate probabilities of pregnancy, live birth, and adverse events from demographics, hormone levels, and prior stimulation responses, improving counseling and treatment, though barriers remain including training-data quality, algorithmic bias, and the need for real-world validation [21,22,28].

3.1. Embryo Selection Using Artificial Intelligence

Embryo selection is an essential, complex IVF step strongly affecting pregnancy and birth outcomes. Conventional morphological grading is highly subjective and variable between embryologists. AI, using large embryo-image datasets and time-lapse video, learns patterns associated with viability and implantation potential, reducing bias and variability; numerous reviews indicate AI predicts embryo morphology and clinical outcomes better than embryologists [25]. Deep learning on time-lapse data identifies subtle morphological and morphokinetic features not easily observed by humans, improving prediction of viability and implantation. Frameworks report median AI accuracy of 75.5% for morphological prediction versus ∼65% for embryologists, and a meta-analysis of AI tools for pregnancy outcomes reported pooled sensitivity 0.69 and specificity 0.62 (AUC 0.70) [25,29-31]. The CNN-based iDAScore family ranks implantation likelihood from time-lapse videos and shows good generalizability across IVF centers, adapting to multimodal learning with images, videos, and clinical data. However, randomized controlled trials remain few; in one RCT, deep-learning selection did not differ from standard morphological assessment for clinical pregnancy, indicating further validation is needed. Explainable AI (XAI) frameworks and methods exploiting the spatiotemporal nature of embryo development aim to improve transparency and clinician acceptance without sacrificing accuracy [26,32-35].

3.2. Cycle Monitoring and Ovulation Prediction

Accurate cycle monitoring and ovulation prediction are key for timing conception and assessing reproductive health. Traditional methods – calendar tracking, basal body temperature (BBT), and urine luteinizing hormone (LH) tests – often lack accuracy, especially with disorders such as PCOS [36]. Wearable devices with ML algorithms continuously monitor heart rate, respiratory rate, and skin temperature to estimate ovulation and the fertile window; a systematic review and Bayesian network meta-analysis reported pooled fertile-window detection accuracy around 0.88, superior to BBT or calendar tracking. ML classifiers using wrist-worn data classified menstrual phases including ovulation with up to 87% accuracy, and skin-temperature/heart-rate algorithms predicted the fertile window and menstruation onset in regular and irregular cycles with AUC ∼0.87–0.89 [37-39]. AI-interpreted salivary ferning via smartphone shows promise for regular and irregular cycles, and non-invasive biosensing combining radar, PPG, and LiDAR with federated AI enables privacy-preserving real-time ovulation prediction. In NC-FET, an AI management algorithm predicted ovulation day with >95% accuracy, guiding intervention timing and improving clinical pregnancy rates [40-43].

4. Role of Artificial Intelligence in Infertility Therapeutics

AI is revolutionizing infertility therapeutics by enabling individualized treatment plans, optimizing drug dosage, and predicting outcomes more accurately than traditional means. Management involves complex

decisions on stimulation procedures, drug dosage, and intervention timing that previously relied on clinician experience and subjective judgment. By leveraging large multidimensional patient data (history, hormone levels, imaging, genetic profiles), AI supports data-driven decisions. A major application is personalizing ovarian stimulation: traditional ART protocols are standardized and ignore individual variability, whereas AI uses AMH, AFC, and BMI to recommend personalized dosing that maximizes mature oocyte yield while lowering OHSS risk, and ML predicts optimal FSH starting doses and trigger timing to improve oocyte yield and IVF success [21,22,29,44]. Limitations remain: model accuracy depends on data quality and diversity, and many datasets are small, single-center, or unrepresentative, affecting generalizability. Ethical issues of data privacy, algorithmic transparency, and bias must be addressed, and large prospective trials are needed to validate AI recommendations across diverse populations [29,45].

4.1. Personalized Treatment Planning

AI and ML have made personalized treatment planning an essential component of infertility care. Traditional ART management, especially IVF, relies on clinician interpretation of large, complex datasets (hormone profiles, imaging, ovarian reserve, semen parameters, prior cycle outcomes), where subjectivity contributes to variable success rates. Using large real-world datasets and predictive models, AI enables individualized interpretation; a review of 112 studies highlighted AI enhancing personalization through individualized stimulation protocols, sperm/oocyte quality assessment, embryo selection, cycle monitoring, and outcome prediction, outperforming conventional methods [46,47]. In male infertility, automated AI sperm analysis using SVMs and neural networks objectively evaluates motility, morphology, and DNA integrity with greater reliability than manual methods, with major implications for patients with azoospermia or oligospermia; AI identifying viable sperm from millions of images in seconds may enable earlier intervention in previously untreatable cases. In ART, deep CNN analysis of time-lapse imaging and morphological patterns improves prediction of embryo viability and supports elective single embryo transfer (eSET), while explainable AI provides interpretable criteria that enhance physician trust and adoption [34,48-50].

4.2. Drug Selection and Dose Optimization

One of the first validated AI uses is ML-derived individualized FSH starting doses, which better align dose with ovarian response, decreasing total gonadotropin consumption while maintaining or improving mature oocyte yield. Retrospective studies show AI-devised doses match clinician recommendations with less total FSH, suggesting cost savings and reduced OHSS risk, supported by real-world AI-assisted clinical decision support systems (CDSSs) showing significant reductions in initial and total FSH dose without compromising laboratory outcomes. Prospective and randomized protocols, including multi-center trials, are evaluating non-inferiority or superiority of ML-based versus clinician-assigned dosing for mature oocyte retrieval and OHSS risk. Advanced models integrate real-time hormone levels and follicular development during controlled ovarian stimulation (COS) to guide both dose and trigger timing, maximizing oocyte maturity and embryo quality [44,51-53]. Beyond gonadotropin dosing, prediction models using ultrasonography and hormonal trajectories fine-tune scheduling and identify potential issues, with imaging feature extraction improving prediction of follicular responses; however, most models are trained on small single-center datasets [20,28]. Pharmacologic choice considers causes such as ovulation disorders, endocrine issues like PCOS, unexplained cases, or prior success; for anovulation, studies favor letrozole over clomiphene citrate for higher live birth and ovulation rates in PCOS. Clomiphene citrate blocks hypothalamic estrogen receptors to enhance GnRH secretion, while letrozole, an aromatase inhibitor (2.5–7.5 mg), inhibits estrogen synthesis to enhance FSH action [54-57]. Dose optimization maximizes efficacy and minimizes harm, especially for injectable gonadotropins in COS, with patient features such as age, BMI, AMH, and antral follicle count determining dose; individualized predictive protocols minimize hypo- and hyper-responses and maximize oocyte yield [58,59]. Pharmacogenetics offers a further direction, as genotypes affecting FSH receptor sensitivity and drug metabolism could enable better personalization once validated [60].

5. Future Perspectives and Emerging Trends

Infertility treatment is shifting from strictly clinical approaches toward lifestyle- and nutrition-based

methods that improve fertility through metabolism, inflammation, and reproduction. Evidence supports dietary intake, systemic inflammation, oxidative stress, gut microbiota, metabolic dysfunction, and epigenetics as significant fertility factors in both sexes, with research moving from isolated nutrients toward holistic dietary patterns. Meta-analyses link pro-inflammatory dietary indices to infertility risk, suggesting anti-inflammatory dietary interventions for preventive care, and population studies associate Mediterranean or low-inflammatory diets with better female fertility [61-63]. Network meta-analyses suggest supplement combinations (e.g., vitamin D + probiotics, coenzyme Q10 + astaxanthin, curcumin + vitamin D) may improve pregnancy rates and embryo quality, and umbrella reviews identify nuanced roles for folate, omega-3, and antioxidants, pointing toward personalized supplementation. Gut microbiota dysbiosis from diet may impair the hypothalamic-pituitary-ovarian axis, promoting inflammation, metabolic dysfunction, and reduced fertility [64,65]. Generative AI and LLMs represent an emerging frontier, synthesizing published research to generate hypotheses, integrate data for real-time decision support, accelerate translational research, and improve physician-patient communication, with early adopters suggesting changes to epidemiologic modeling, risk assessment, and patient education [66].

5.1. AI-Based Digital Twins in Reproductive Health

AI-powered digital twin (DT) technology is becoming a major force in patient-centered care through personalizing, predicting, and preventing illness. A digital twin is a virtual, continuously updated representation of a physical system that uses real-world data to model outcomes under changing conditions, allowing providers to estimate event probabilities, personalize treatment, and make decisions without patient risk. In reproductive medicine, DTs integrate AI systems, real-time biosensors, multimodal data streams (wearables, hormone levels, imaging, clinical history), and simulation models to individualize infertility treatment and support pregnancy; emerging evidence suggests DTs may enhance diagnostic accuracy, improve embryo selection, optimize hormone therapies, and model maternal-fetal interactions [67,68]. A systematic review found DT use in fertility and childbearing still early but promising, spanning embryo assessment, IVF modeling, placental simulation, drug distribution, and delivery monitoring, with most applications needing further validation. AI-enhanced hormone monitoring with DTs is being explored for personalization; one prototype, a Digital Twin–Enabled Smart Health Monitoring System, combines continuous hormone monitoring (e.g., 17β-estradiol) with wearable biosensing to model menstrual cycles and predict ovulation more precisely than periodic clinical tests. Related work uses field-effect-transistor (FET) sensors for real-time hormone measurement feeding decision-support twins, while in-silico placental models combined with patient-specific data aim to predict pregnancy complications such as preeclampsia and placental insufficiency [68-70].

5.2. Role of AI in Preventive Reproductive Healthcare

A key AI use is prevention and treatment of infertility. Traditional evaluation via hormonal testing, ultrasound, and semen analysis suffers from subjectivity and inter-operator variability. Systematic reviews show ML and DL models assess ovarian reserve, semen quality, and IVF outcomes more accurately, using demographic, biochemical, and imaging data to outperform traditional statistics; a review of 112 studies reported significant improvement in ovarian reserve assessment and embryo selection with less variability in reproductive imaging and workflow [71]. In ART, deep learning on time-lapse embryo images improves consistency of morphology and viability assessment, potentially raising implantation and pregnancy rates, while AI personalizes stimulation through gonadotropin dosing and cycle-specific adjustments. Beyond ART, AI-powered CDSSs incorporate patient history, ultrasound, EHRs, and physiological readings to assess gestational diabetes, preeclampsia, preterm delivery, and miscarriage risk [29,72]. A scoping review found widespread AI application across sexual and reproductive health – screening, diagnostic assistance, population health trends, and mHealth tools and chatbots providing education and remote preventive services regardless of geography [73]. Challenges remain: algorithms must be transparent to avoid “black box” medicine, homogeneous training data risks bias and limited generalizability, and clinical translation needs multi-center validation, standardized reporting, and attention to privacy, consent, and equity. Emerging research merges multi-omics (genomics, proteomics, metabolomics) with ML to identify biomarkers of early reproductive decline before symptoms appear [74,75,76]. Predictive AI models using age, hormone levels, ultrasound, and embryo appearance predict IVF outcomes more accurately than

clinician judgment alone, stratifying patients by risk of implantation failure or early miscarriage so treatments can be adjusted sooner [77]. Narrative reviews show CDSSs integrating mathematical models, calculators, and ML into clinical workflow help identify infertility causes, optimize treatment, and monitor cycles in real time, detecting subtle hormonal or follicular changes for early warning [79]. Reviews also find AI roughly 90% accurate on average at assessing sperm and embryo quality, improving IVF results by reducing subjective judgment and speeding decisions, supporting its preventive use [80].

6. Conclusion

AI is revolutionizing reproductive medicine by enabling predictive, preventive, and personalized care and moving away from reactive management of infertility. The evidence reviewed shows AI can enhance diagnostic precision and objectivity through automated semen analysis, hormonal profiling, and improved imaging analysis. In ART, AI supports embryo selection, cycle monitoring, and outcome prediction, improving efficiency and consistency while reducing bias and enabling individualized decisions. Combined with clinical, biomarker, imaging, and wearable data, AI-driven CDSSs may support prediction and prevention of poor ovarian response, implantation failure, and adverse pregnancy outcomes, enabling rapid intervention, counseling, and optimized protocols. Emerging technologies such as digital twins, multi-omics integration, and real-time biosensing will further enable modeling of reproductive function and treatment response before clinical sequelae occur. Major obstacles to clinical implementation include data variability, algorithmic bias, limited model transparency, and ethical and consent issues; standardized datasets, robust models, and thorough multi-center testing are required. Carefully implemented, AI in reproductive medicine can significantly enhance outcomes, reduce burden, and improve preventive reproductive healthcare.

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